

# A TEST TRACK PERFORMANCE EVALUATION OF CURRENT PRODUCTION LIGHT VEHICLE ANTILOCK BRAKE SYSTEMS

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## ABSTRACT

*A Test Track Performance Evaluation of Current Production Light Vehicle Antilock Brake Systems* was conducted to compare the braking performance of vehicles equipped with present-day antilock brake systems (ABS) with the performance of the same vehicle without ABS (simulated conventional brakes) over a large range of driving conditions. The motivation for this work was to attempt to find situations and/or conditions in which ABS-equipped vehicles did not perform as well as their non-ABS counterparts, not to compare vehicles or antilock brake systems to one another.

The braking performance of nine high production passenger vehicles was evaluated in seventeen stopping situations. These situations were comprised of various road surfaces, driver steering actions, and vehicle speeds. Testing was performed with lightly and heavily laden vehicles, with the ABS active and disabled, and used two brake pedal application techniques. The selected vehicles included at least one ABS from eight current ABS manufacturers.

This study found that for most stopping maneuvers on most surfaces, ABS-assisted full pedal brake application stops were shorter than those made with the ABS disabled. Additionally, vehicular stability during these maneuvers was almost always superior with the assistance of ABS. The one systematic exception was on loose gravel where stopping distances increased by an average of 27.2 percent overall.

## INTRODUCTION

Antilock brake systems (ABS) first appeared in the U.S. during the late 1960's. By the late-80's four-wheel ABS had become standard equipment on a limited number of sport and luxury-oriented automobiles and light trucks. In recent years, ABS has become more

common and is now standard equipment on many high production passenger cars and light trucks. According to ITT Automotive, 62 percent of 1996 model year vehicles were equipped ABS [1].

The principal reason for equipping passenger cars and light trucks with ABS is to increase safety. Years of watching the enhanced lateral stability and improved stopping performance of vehicles equipped with ABS on the test track initially convinced brake experts that the widespread introduction of ABS should significantly reduce the number of crashes, and the resulting injuries and fatalities, that occur on our nation's highways.

To determine whether the experts' belief that the introduction of ABS would increase safety was indeed true, a number of statistical analyses of crash databases have been performed over the past several years. These analyses suggest that, for automobiles, the introduction of ABS has produced net safety benefits much lower than originally expected for ABS-equipped vehicles [2,3,4,5]. For example, Kahane found that while the involvement of ABS-equipped automobiles in fatal multi-vehicle crashes on wet roads was reduced by 24 percent, fatal single vehicle crashes increased by 28 percent [5]. This increase in single-vehicle crashes almost completely offsets the safety advantage an ABS-equipped automobile has over its conventionally-braked counterpart. Similar results were found in the other automobile crash database studies. Note that the anticipated safety benefits due to ABS *were* seen in light truck (rear wheel ABS only) crash data studies.

To learn why the crash data studies did not find the anticipated increase in safety for ABS-equipped automobiles, the National Highway Traffic Safety Administration (NHTSA) developed its Light Vehicle ABS Research Program. This comprehensive program attempts, in a series of tasks, to examine all plausible reasons why the crash data studies do not show that ABS has improved automobile safety. NHTSA's

Motor Vehicle Safety Research Advisory Committee's (MVSAC) ABS Working Group, comprised of government and industry participants, commented on, and approved of, the research program's test plan. The group's contribution is much appreciated.

## **BACKGROUND AND STUDY OBJECTIVES**

*A Test Track Performance Evaluation of Current Production Light Vehicle Antilock Brake Systems* (Task 4 of the eight NHTSA Light Vehicle ABS Research Program tasks) was conducted to compare the braking performance of vehicles equipped with present-day antilock brake systems to the performance of the same vehicle without ABS over a large range of driving conditions. The braking performance of nine vehicles, each equipped with a different manufacturer's ABS, was evaluated in seventeen stopping situations involving a variety of road surfaces, driver steering actions, and vehicle speeds. Testing was performed with lightly and heavily laden vehicles and with the ABS active and disabled.

The motivation for this work was to attempt to find situations and/or conditions in which vehicles equipped with ABS would not perform as well as their non-ABS (conventionally braked) counterparts. While ABS stopping performance has been measured by many groups over many years, there is a possibility that poor performance on some unusual surface or during some maneuver may have been overlooked. If such conditions could be found, they may explain the apparent increase in single-vehicle crashes of ABS-equipped automobiles. Note that it was not the intention of this work to compare vehicles or antilock brake systems to one another.

ABS performance evaluations have been conducted prior to this study by NHTSA's Vehicle Research and Test Center (VRTC) in East Liberty, Ohio [7,8]. In these earlier evaluations, a number of vehicles equipped with a variety of antilock brake systems were tested over a range of road surfaces and stopping maneuvers. Both of these earlier studies found that ABS improved vehicular stability under braking, especially when a difference in road friction coefficients existed between the left and right sides of the vehicle. Four-wheel antilock brake systems reduced the tendency of the vehicles to yaw excessively and allowed the driver to maintain steering control while braking. Rear-wheel-only ABS was found to only enhance braking stability, as these systems are not designed to modulate the longitudinal slip of the front wheels during braking. Therefore, although rear-wheel-

only ABS prevented excessive yaw, no steering control benefits were provided to the driver during braking.

The earlier studies also found that stopping distances on hard, paved test surfaces either stayed the same or were reduced for four-wheel ABS-equipped vehicles. Stopping distance increases of over 25 percent occurred in several cases on gravel. In some cases rear-wheel ABS slightly reduced stopping distances and, in other cases, increased it.

The current ABS performance evaluation differs from those previously performed by VRTC in several significant ways. First, the vehicles tested have newer antilock brake systems than those tested in the earlier studies. Second, the vehicles were tested on more surfaces than in the past. Third, the vehicles were tested on a number of surfaces having sudden coefficient of friction transitions (past VRTC testing has found that some antilock brake systems have problems dealing with such transitions). Fourth, the vehicles were tested in additional maneuvers. Again, past VRTC testing found that some systems exhibited braking deficiencies while performing certain maneuvers (e.g., hard braking while in a curve).

## **TEST PROCEDURE**

### **Test Vehicles**

The test vehicle fleet included a diverse range of high production passenger vehicles, ranging from compact cars to sport utility vehicles. The selected vehicles included at least one ABS from eight current ABS manufacturers.

Eight vehicles were equipped with "add-on" ABS packages, and one was "integrated." Although the functionality of these configurations is identical, the integrated ABS physically combines the master cylinder with the hydraulic control unit (HCU) into one component. The master cylinder and HCU of the add-on systems, however, are joined only by the brake lines run between them.

The antilock brake systems in seven of the nine test vehicles used four wheel speed sensors, one at each wheel. The two rear-wheel drive vehicles utilized three wheel speed sensors, one positioned at each front wheel and one in the rear differential. Four vehicles were equipped with four-channel antilock brake systems that independently modulated the front and rear brake line pressures at each wheel. The five remaining test vehicles were equipped with three-channel antilock brake systems that also modulated the two front line pressures independently, but modulated

the line pressures at the right rear and left rear together. The ABS configurations of each test vehicle are listed in Table 1.

**Table 1.**  
**Test Vehicle ABS Configuration**

Vehicle	ABS Configuration
A	add-on; four-sensor, four-channel
B	integrated; four-sensor, four-channel
C	add-on; four-sensor, four-channel
D	add-on; four-sensor, three-channel
E	add-on; four-sensor, four-channel
F	add-on; four-sensor, three-channel
G	add-on; four-sensor, three-channel
H	add-on; three-sensor, three-channel
I	add-on; three-sensor, three-channel

It should be noted that this study originally included only eight test vehicles. However, as the eighth vehicle was approaching test completion, seemingly odd ABS behavior was noted in a vehicle being driven in another NHTSA test program. When a large braking input was applied during the program's steer-and-brake maneuver, the brake pedal would rise quickly and remain firm against the driver's foot (due to ABS activation) at high lateral acceleration. Although this is not necessarily a negative feature, the pedal rise also coincided with the sensation that the vehicle was not generating the anticipated braking force and vehicle deceleration.

Preliminary braking maneuvers were conducted and confirmed the previously noted pedal feel and perceived stopping distance increase whenever a high lateral acceleration was established prior to a large brake pedal force input. Such behavior was not observed in the eight vehicles of the original test matrix. Recalling that the motivation for this study was to find situations where the use of ABS resulted in some form of stopping deficiency (when compared to the same vehicle equipped with conventional brakes), it was determined that the vehicle should be subjected to the entire ABS hardware evaluation test matrix as a ninth vehicle.

## Instrumentation

Table 2 provides a list of instrumentation installed in each test vehicle. The fifth wheel assembly was mounted to the rear bumper attachment points and transmitted vehicle speed and distance signals to a digital performance monitor positioned on the dashboard. The monitor's trigger input was activated by the brake light switch to freeze the initial vehicle speed and zero vehicle position when the brake pedal was depressed. The speed and position measured by the fifth wheel were recorded as a function of time with an update rate of 100 Hz by a digital on-board data acquisition system.

Brake line pressure transducers were connected between the hard and flexible brake lines to transmit the line pressure seen at each wheel downstream of the ABS HCU. Direct current tachometers attached to each wheel monitored wheel lockup by measuring individual wheel speeds. A load cell was attached to the brake pedal to transmit applied force. Two accelerometers and a rate sensor, positioned at the vehicle's center of gravity to minimize vehicle pitch and roll effects, measured lateral/longitudinal acceleration and yaw rate, respectively. To signal a desired point within a braking maneuver, an optical pickup sensor was installed on the vehicle's front license plate bracket. All data measured by this instrumentation were recorded, as a function of time, by the on-board data acquisition and each channel was sampled at a rate of 100 Hz.

## Loading

Each vehicle was tested at two loading conditions: lightly laden and at its Gross Vehicle Weight Rating (GVWR). Lightly laden was defined as the vehicle curb weight (with a full tank of fuel) plus the test driver and instrumentation. The GVWR condition involved loading the vehicle to the maximum vehicle weight recommended by the manufacturer, and was achieved by ballasting the test vehicle with sand bags distributed so that the axle weights were in proportion with the Gross Axle Weight Ratings (GAWR).

## Test Matrix

Table 3 summarizes this study's test matrix. Testing was performed with ABS and with the ABS disabled using two pedal application techniques. The matrix included nine different test surfaces and five

different stopping maneuvers, each performed with the vehicles lightly laden and at GVWR. To disable the ABS, an electrical fuse in the test vehicle's fuse box

was replaced with a fused toggle switch to interrupt power to the ABS electronic control unit, solenoid valves, or pump motor.

**Table 2.**  
**Instrumentation**

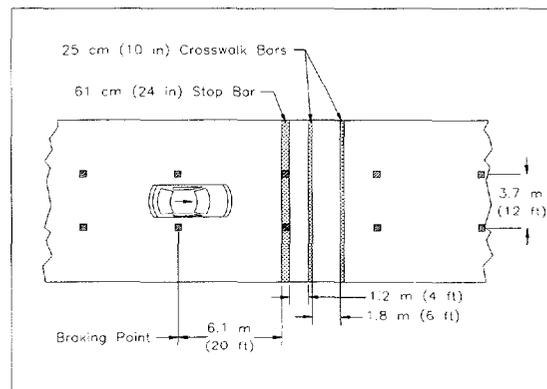
Description	Measured Data	Vehicle Location
Accelerometer	Lateral and longitudinal acceleration	Positioned at center of gravity
Fifth wheel	Vehicle speed and distance traveled	Rear bumper attachment points
Load cell	Brake pedal force	Brake pedal
Pressure transducers	Brake line pressure seen at each caliper or drum	Between hard and flexible brake lines at each corner
Rate sensor	Yaw rate	Positioned at center of gravity
Optical pickup sensor	Event trigger	Front license plate bracket
Wheel tachometers	Individual wheel speed	Each wheel via wheel mounting lugs or lug nuts

**Test Surfaces**

Nine surface types were used for this study: dry asphalt, wet asphalt, dry concrete, wet polished concrete, wet epoxy, grass, loose gravel, wet Jennite, and an epoxy/sand surface. The polished concrete was designed to simulate a heavily worn road and was created by troweling and polishing with a floor polisher. The epoxy pad (asphalt covered with a coating typically used on factory floors) and wet Jennite (a coal tar emulsion asphalt sealer trade name) surfaces simulated badly worn wet roadways. Due to severe deterioration, the epoxy pad was resurfaced before the final two vehicles were evaluated, reducing the peak coefficient of friction and slide skid numbers by over one third.

This study also utilized a specially designed ABS test course. Created in mid 1996, the course was designed to evaluate ABS performance on a series of simulated real world test pads. An antilock brake system's ability to recover vehicle deceleration after returning to smooth asphalt from a given pad were observed. Each of the four ABS test course pads were wet during testing. Test Pad #0 was used to determine vehicle stopping distance for the wet, unperturbed asphalt surface of the course. Test Pad #1 included one Jennite strip 61 cm (24 in) wide applied to the asphalt to simulate a stop bar found at an intersection with a stop sign or traffic light. Test Pad #2 (Figure 1)

simulated a stop bar followed by two bars to mark crosswalk area, and was oriented as follows: a 61 cm (24 in) wide Jennite stop bar, four feet of asphalt, a 25 cm (10 in) Jennite strip, six feet of asphalt, and a second 25 cm (10 in) Jennite strip. Test Pad #3 (Figure 2) consisted of two adjacent artificial potholes, one in each wheel track, constructed from steel frames set into concrete and treated with an epoxy/sand surface. The wet epoxy/sand surface provided a coefficient of friction very similar to dry pavement.

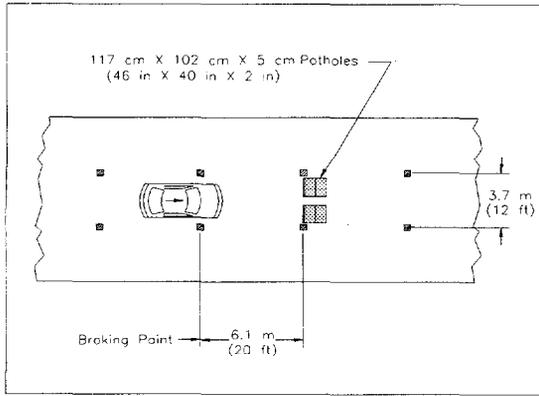


**Figure 1. ABS Test Pad #2.**

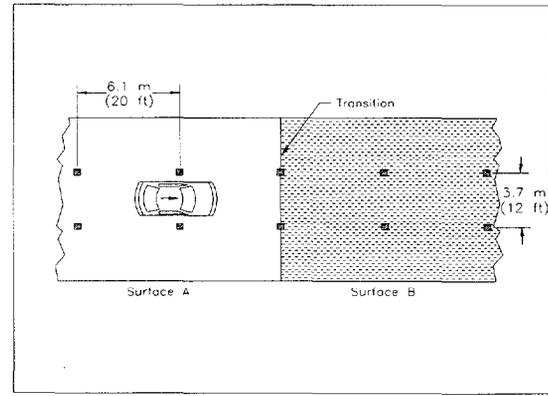
**Table 3.  
Light Vehicle ABS Test Matrix**

Surface	Nominal ASTM Skid No. (Peak/Slide)	Maneuver	Speed
Dry Concrete	90/75	Straight Line	97 km/h (60 mph)
Wet Polished Concrete	unknown/60	Straight Line	64 km/h (40 mph)
Wet Asphalt	85/65	Straight Line	80 km/h (50 mph)
Wet Jennite	30/10	Straight Line	64 km/h (40 mph)
Grass	unknown	Straight Line	40 km/h (25 mph)
Loose gravel	unknown	Straight Line	56 km/h (35 mph)
Wet Asphalt to Wet Jennite	(85/65) to (30/10)	Transition	64 km/h (40 mph) Transition at 40 km/h (25 mph)
Wet Jennite to Wet Asphalt	(30/10) to (85/65)	Transition	56 km/h (35 mph) Transition at 40 km/h (25 mph)
Wet Asphalt across corner of Wet Epoxy to Wet Asphalt	(85/65) across corner of (20/3)* to (85/65)	Transition	64 km/h (40 mph) Transition at 40 km/h (25 mph)
ABS Test Pad #0	85/65	Transition	64 km/h (40 mph)
ABS Test Pad #1	(85/65) to (30/10) to (85/65)	Transition	64 km/h (40 mph)
ABS Test Pad #2	(85/65) to (30/10) to (85/65) to (30/10) to (85/65) to (30/10) to (85/65)	Transition	64 km/h (40 mph)
ABS Test Pad #3	(85/65) to unknown to (85/65)	Transition	64 km/h (40 mph)
Wet Asphalt/Wet Epoxy	(85/65) / (20/3)*	Split-Mu	48 km/h (30 mph)
Dry Asphalt	90/80	Curve (91.4 m radius)	80 km/h (50 mph)
Wet Jennite	30/10	Curve (152.4 m radius)	64 km/h (40 mph)
Dry Asphalt	90/80	J-turn	80 km/h (50 mph)

\* The actual skid numbers of the epoxy surface exceeded the nominal specifications for the first seven test vehicles. The average peak and slide values recorded during this time interval were 52 and 14, respectively.



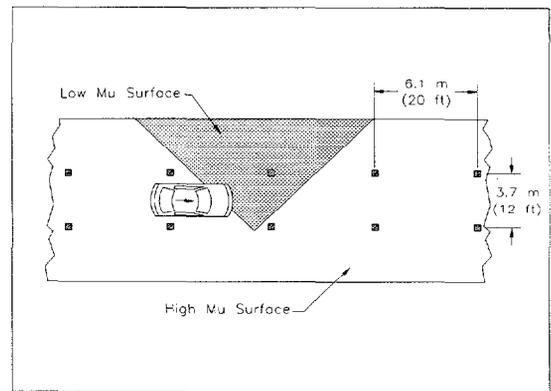
**Figure 2. ABS Test Pad #3.**



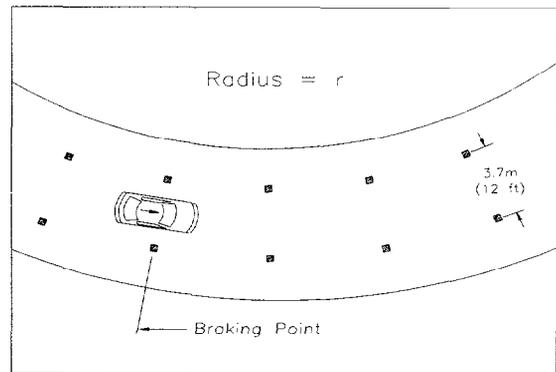
**Figure 3. Perpendicular transition.**

**Maneuvers**

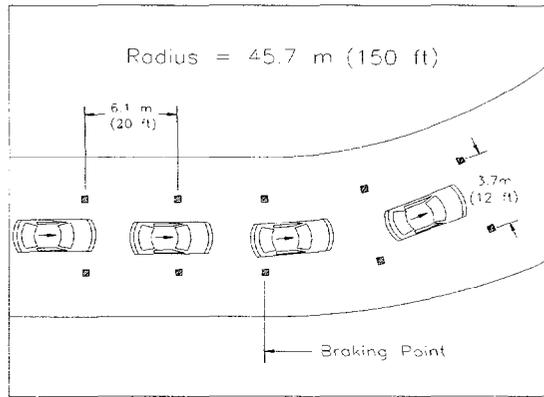
This study involved five stopping maneuvers: 1) straight line, 2) split-mu, 3) transition, 4) curve, and 5) J turn. Straight line maneuvers involved stopping on a uniform coefficient surface. Split-mu maneuvers required straight line stopping over a surface with split (side-to-side) frictional coefficients. Transition maneuvers (Figures 3 and 4) were made while the driver applied a constant brake application as the vehicle traveled over surfaces with changing frictional coefficients. The initial speed and brake application points were chosen such that the initial surface transition would be accomplished at approximately 40 km/h (25 mph). Braking in a curve of known radius (Figure 5) and the J-turn, a maneuver designed to observe how a vehicle responded to a sudden and severe steering input quickly followed by a brake application (Figure 6), each occurred on surfaces with uniform frictional coefficients. All stopping lanes were 3.7 m (12 ft) wide, marked with cones spaced 6.1 m (20 ft) apart. For each maneuver, the test driver was allowed to make steering inputs as necessary to maintain lane position.



**Figure 4. Offset transition.**



**Figure 5. Braking in a turn.**



**Figure 6. J-turn maneuver.**

### Speed

The target speeds specified for each maneuver were chosen to reflect available space, real world utility, and safety considerations. Although these speeds are listed in Table 3, the actual speeds observed while testing varied slightly. As a result, the actual stopping distances were adjusted to represent the distances of those maneuvers as if they had been run at the target speed using the following expression [12]:

$$s' = \frac{v_{target}^2}{v_{actual}^2} \times s_{actual}$$

where

$$s' = \text{corrected stopping distance}$$

$$v_{target} = \text{target initial vehicle velocity}$$

$$v_{actual} = \text{actual initial vehicle velocity}$$

$$s_{actual} = \text{actual stopping distance}$$

### Brake Applications

Two brake application techniques were used in this study: 1) "panic" and 2) "best effort." Panic applications involved a rapid force application of over 667 N (150 lbs) to the brake pedal. These stops were expected to be very repeatable, therefore only three panic stops for each case (ABS and disabled ABS) were conducted. Best effort stops required the driver to modulate pedal effort as necessary to achieve the

shortest possible stopping distance while maintaining vehicle control and lane position. No more than one wheel per axle was permitted to lock during best effort stops to ensure vehicular stability was maintained. To allow time for driver familiarization with a given vehicle's braking ability, six best effort stops were run for the maneuvers that required them. To eliminate driver variability effects, only one professional test driver with 17 years experience served as driver for all testing conducted for this study.

With the exception of the transitional stops on the ABS test course, each transition maneuver only included three ABS-assisted stops. Transitional maneuvers were designed to evaluate ABS reaction times and responses to sudden changes in roadway frictional coefficients. For this reason, it was unnecessary for disabled ABS stops to be conducted.

Best effort stops with the ABS disabled were not performed over the ABS test course transitions. Three disabled ABS panic stops, however, were included to facilitate an ABS stopping performance comparison.

Three ABS and three disabled ABS panic stops were tested on the grass and loose gravel surfaces. Data collected from best effort stops made on these surfaces was assumed to have few significant real world applications. Best effort stops, therefore, were deemed unnecessary on grass and gravel.

Braking in a curve and J-turn maneuvers did not require panic stops with the ABS disabled as it was expected that the vehicles would quickly lock their front wheels and skid out of the intended lane. Disabled ABS panic stops were likewise omitted from wet asphalt, dry asphalt, wet polished concrete, and dry concrete maneuvers due to the excessive tire wear executing such stops was expected to incur. For these seven maneuvers only three ABS-assisted and six best effort disabled ABS stops were conducted.

## TEST TRACK RESULTS

### Comments on the Reporting of ABS Performance Results

The results reported in this section used stopping distance and vehicle stability as measures of braking performance. A vehicle yawing out of control with its wheels locked may stop in a very short distance, while a stable vehicle (its directional control maintained throughout the duration of the stop) may require a very long distance to complete its stop. Each condition presents different safety concerns and demonstrates why stopping distance and directional stability must be

evaluated together when discussing ABS performance.

A number of charts provide stopping distances observed with fully laden test vehicles in this section of the report. If a legend is not included with a given chart, the reported stopping distances were collected using ABS-assisted panic brake applications. If a legend is provided, “ABS” refers to an ABS-assisted panic stop, “Full Pedal” refers to a panic stop with the ABS disabled, and “Best Effort” refers to test driver modulated stops made with the ABS disabled.

Thirteen of the eighteen stopping maneuvers required ABS-assisted stopping distances to be compared to those measured with the ABS disabled. To facilitate this comparison, the following equation was used:

*ABS Stopping Distance Improvement* =

$$\frac{SD_{ABS\ disabled} - SD_{ABS}}{SD_{ABS\ disabled}} \times 100\%$$

where

$SD_{ABS\ disabled}$  = stopping distance achieved with an ABS disabled (panic or best effort)

$SD_{ABS}$  = stopping distance achieved with the assistance of an ABS

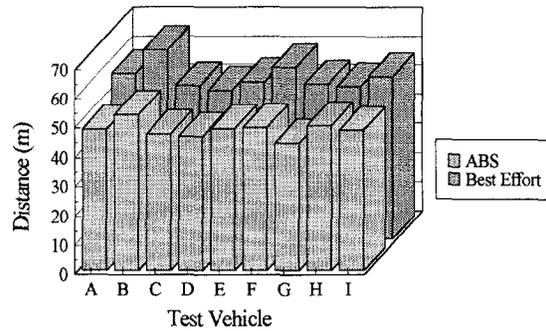
Although the ninth test vehicle was to be subjected to the complete ABS test matrix, an unforeseen event occurred during the single lane change maneuver that prohibited the completion of lightly laden testing. For this reason, many charts for this loading condition include stopping distances for eight vehicles only.

### Straight Line Stops on Uniform Coefficient Surfaces

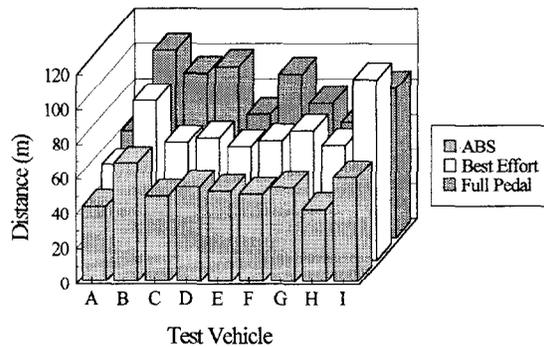
A panic brake application used in conjunction with ABS resulted in the shortest straight line stopping distances on the dry concrete and wet polished concrete surfaces for each of the eight test vehicles at both loading conditions (Figure 7 summarizes the GVWR stopping distances made on dry concrete). Antilock brakes also facilitated the shortest stopping distances on the wet Jennite (Figure 8) and wet asphalt surfaces for each vehicle when fully laden.

On wet asphalt, for the lightly laden loading condition, eight of the nine vehicles stopped in the shortest distance with ABS. The test driver’s minimum best effort stopping distances were 4.9 percent less than the ABS-assisted stops with vehicle “H” on wet

asphalt. On wet Jennite, for the lightly laden loading condition, seven of the eight vehicles stopped in the shortest distance with ABS. The test driver’s minimum best effort stopping distances were 9.2 percent less than the ABS-assisted stops with vehicle “A” on wet Jennite. Lightly laden straight line stops on wet Jennite were not performed with test vehicle “I”.



**Figure 7.** Straight line stopping distances observed on dry concrete. Test vehicles were fully laden to their respective GVWRs.



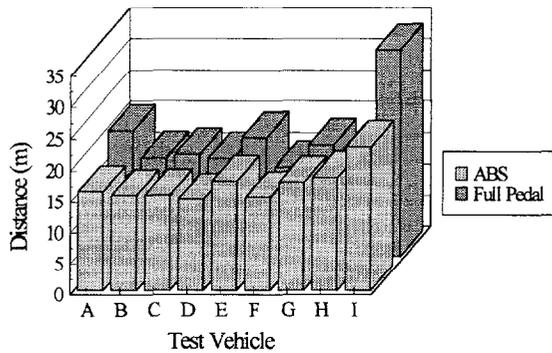
**Figure 8.** Straight line stopping distances observed on wet Jennite. Test vehicles were fully laden to their respective GVWRs.

### Straight Line Stops on Off-road Surfaces

**Grass** - Seven of the nine test vehicles laden to GVWR stopped in the shortest distance when a panic brake application was used in conjunction with ABS on the grass surface (Figure 9). The ABS-assisted stops were an average of 6.9 percent shorter than those made with the ABS disabled at GVWR. This percentage

drops to 4.0 percent if the stopping distances of vehicle "I" are not included in this comparison. Unlike for the other vehicles, the grass surface was very wet when test vehicle "I" was evaluated, and in some areas standing water was present. This may explain the 30.1 percent longer full pedal application stopping distance with the ABS disabled, when compared to the distance recorded with the assistance of ABS.

Conversely, six of the eight test vehicles stopped in the shortest distance with a panic brake application and disabled ABS when lightly laden. At this loading condition the stopping distances were an average of 7.1 percent longer than the ABS-assisted stops across the eight vehicle test group. Test vehicle "I" was not tested



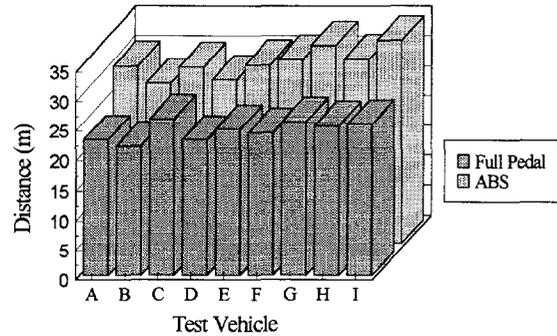
**Figure 9.** Straight line stopping distances observed on grass. Test vehicles were fully laden to their respective GVWRs. Note: the grass was very wet when the braking performance of vehicle "I" was evaluated.

on the grass when lightly laden.

**Loose Gravel** - On loose gravel, each of the nine vehicles stopped in the shortest distance with a panic brake application and disabled ABS, regardless of loading condition. Stops made on the gravel were lengthened considerably when the ABS was active: 24.6 percent when the test vehicles were fully laden (Figure 10) and 30.0 percent when lightly laden. The fully laden percentage drops to 23.4 percent if the stopping distances of vehicle "I" are not included in this comparison. As with the grass surface, the gravel was very wet when test vehicle "I" was evaluated, unlike for the other vehicles. This may explain the 33.7 percent stopping distance increase with ABS when compared to the distance observed with the ABS disabled.

The ABS-induced stopping distance increase may be best explained by examining the tire-to-roadway

surface interaction during the braking maneuver. It is generally accepted that the plowing of a vehicle's tires into a deformable surface such as loose gravel generates greater stopping forces than if the wheels were allowed to continue to roll over the surface (as in an ABS-assisted stop). Stopping distances made over the gravel surface therefore represent an inherent ABS design compromise. To preserve the driver's ability to maintain directional control of the vehicle while braking, the wheels must not be allowed to lock. By preserving this control, however, stopping distances made over the loose gravel test surface were extended.

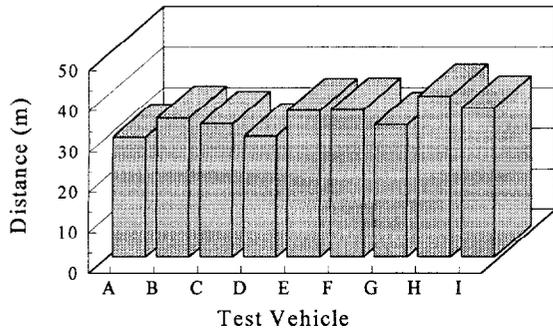


**Figure 10.** Straight line stopping distances observed on loose gravel. Test vehicles were fully laden to their respective GVWRs. Note: the gravel was wet when the braking performance of vehicle "I" was evaluated.

### Transition Surface Braking

The transitional stopping maneuvers were designed to detect gross deficiencies in ABS performance through the observation of unusually long stopping distances and vehicle instability. For each of the nine vehicles, evaluated over three transitions, no apparent shortcomings were revealed. Figure 11 presents typical results. This figure, shows the stopping distances recorded on the wet asphalt/wet Jennite transition surface for the test vehicles at their respective GVWRs. **ABS Test Course Braking**

Each of the nine test vehicles, under both loading conditions, stopped in the shortest distance when the test driver utilized a panic brake application with ABS on Test Pad #0, #1, and #2. On Test Pad #3, eight vehicles stopped in the shortest distance using ABS-assisted panic brake applications, as shown in Figure 12 for the GVWR case (the braking performance of test vehicle "I" was not evaluated on this surface). When

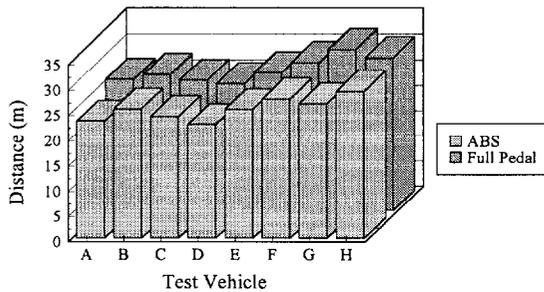


**Figure 11. Straight line stopping distances observed on the wet asphalt/wet Jennite transition surface. Test vehicles were fully laden to their respective GVWRs.**

lightly laden, the shortest stopping distance observed on ABS Test Pad #3 for vehicle "H" occurred when the driver utilized a panic brake application with the ABS disabled. In this case the ABS-assisted panic stop increased the vehicle's stopping distance slightly (2.0 percent) over the disabled ABS panic stop.

### Split-mu Surface Braking

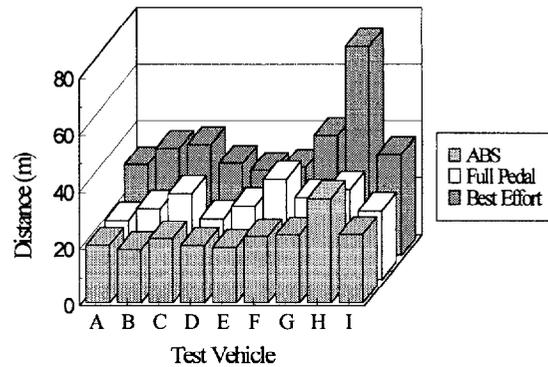
Under both loading conditions, seven of the nine test vehicles achieved the shortest wet asphalt/wet epoxy split-mu stopping distances when the driver used an ABS-assisted panic brake application (see Figure 13 for the fully laden results). When the ABS was disabled and a panic brake input applied, each test vehicle deviated from its stopping lane by yawing out of control (in fact, test vehicle "F" spun 180° for both loading conditions). With ABS, however, the driver



**Figure 12. Straight line stopping distances observed on ABS Test Pad #3 (wet). Test vehicles were fully laden to their respective GVWRs. Vehicle "I" braking performance was not evaluated.**

had no problem maintaining control of each vehicle while braking during the maneuver. These results provide a clear demonstration of how beneficial the assistance of ABS was for this test condition.

The shortest stopping distances for vehicle "H" and "I" were achieved with a panic brake application and disabled ABS. For vehicle "H", the disabled ABS panic stops provided lightly laden and fully laden stopping distances 29.3 percent and 16.5 percent shorter than the ABS-assisted stops, respectively. The same brake application and disabled ABS also resulted in the shortest stopping distances for vehicle "I", although with much less difference when lightly laden. The disabled ABS panic stops provided lightly laden and fully laden stopping distances 13.3 percent and 0.8 percent shorter than the ABS-assisted stops,



**Figure 13. Straight line stopping distances observed on the wet asphalt/wet epoxy split-mu surface. Test vehicles were fully laden to their respective GVWRs. Note: the epoxy surface was reconditioned prior to the brake performance evaluation of vehicles "H" and "I".**

respectively, for test vehicle "I". Both of these vehicles, however, deviated nearly 3 m (10 ft) from their 3.7 m (12 ft) wide stopping lane, under each loading condition, with the ABS disabled due to yaw induced by the lane's two frictional coefficients.

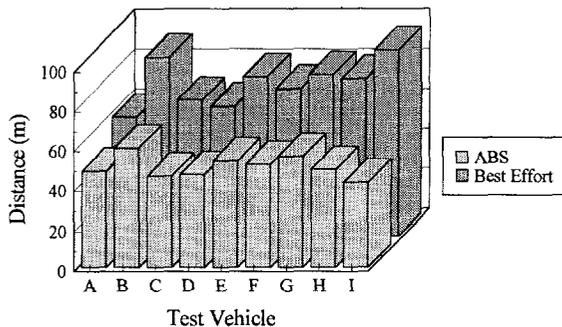
The large stopping distance differences between the ABS-assisted and best effort stopping distances for vehicle "H" were most likely due to the extremely low frictional coefficient of the resurfaced epoxy pad and the test driver's unfamiliarity with its characteristics. The surface made it much more difficult for the test driver to prevent wheel lock up through brake force modulation with this vehicle than with those driven prior to it. As the driver became more familiar with the surface, after vehicle "H" testing was complete, the

driver was able to better modulate pedal applications to optimize braking. This is indicated by the significant decrease in the ABS-assisted/non-ABS best effort stopping distance differential for vehicle "I" when compared with the results obtained from vehicle "H".

### Braking in a Curve

Two tests involved braking in a curve of known radius: stops made on the wet Jennite 152.4 m (500 ft) radius curve and dry asphalt 91.4 meter (300 ft) radius curve. None of the test vehicles yawed out of control and, with one exception, stopping distances on the wet Jennite curve were found to be shortest with ABS-assisted panic applications at both loading conditions (Figure 14). The stopping distance achieved by test vehicle "A" using a best effort pedal application was 3.7 percent shorter than the comparable ABS-assisted distance on the wet Jennite curve when lightly laden. Note that test vehicle "I" was not evaluated on this curve when lightly laden.

Eight of the nine test vehicles were stopped in the shortest distances using ABS-assisted panic brake applications on the dry asphalt curve (Figure 15). This trend was not observed for test vehicle "I", as its ABS-assisted stops were observed to be longer than the driver's best efforts when lightly laden and at GVWR, 22.5 percent and 11.4 percent, respectively. Analysis of vehicle "I's" braking performance indicated that when a panic brake input was applied while the vehicle was experiencing a high lateral acceleration, the ABS would release brake line pressure at all four wheels and hold it very low during the first few seconds of the braking maneuver. As the vehicle scrubbed off speed, line pressures were gradually allowed to build. It was not until late in the braking maneuver that brake line pressures were allowed to increase to a level great



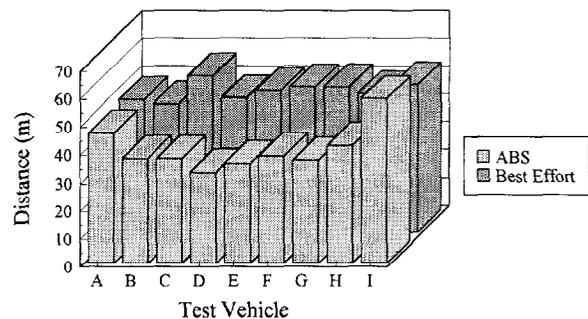
**Figure 14. Stopping distances observed on the 152.4 m (500 ft) wet Jennite curve. Test vehicles were fully laden to their respective GVWRs.**

enough to significantly affect the vehicle's longitudinal deceleration. It should be noted that test vehicle "I" was the only vehicle whose ABS included the capability to monitor the vehicle's lateral acceleration. Further investigation is necessary to determine whether this feature contributed to the apparently extended stopping distances.

### J-turn Stopping Maneuver

The J-turn maneuver was designed to observe ABS braking performance while a test vehicle was undergoing hard cornering. Each ABS prevented the test vehicles from yawing out of control, and allowed seven of the nine test vehicles to perform as expected. Vehicles "C" and "I" did exhibit noteworthy braking behavior (see Figure 16 for the fully laden vehicle stopping distances).

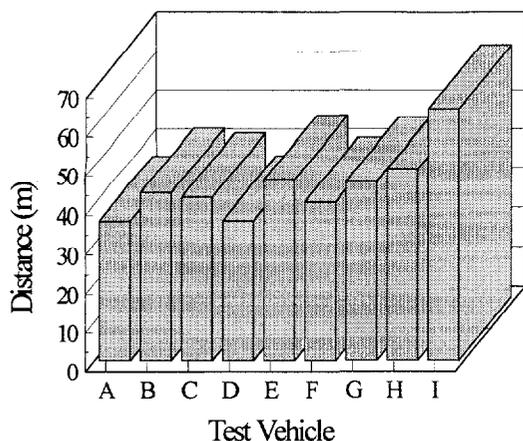
Test vehicle "C" deviated an average of 2.5 m (8.3 ft) from its intended stopping lane in each of the three ABS-assisted panic stops when lightly laden. This vehicle's stopping distances were not noticeably extended, however, and the ABS was not considered to



**Figure 15. Stopping distances observed on the 91.4 m (300 ft) radius dry asphalt curve. Test vehicles were fully laden to their respective GVWRs.**

be responsible for this occurrence. For this case, it was believed that the lateral road holding capacity of the test vehicle was exceeded as it entered the J-turn, inducing understeer. The understeer condition subsided as the vehicle was slowed, and there was no excessive yaw present throughout the stop.

When fully laden, test vehicle "I's" J-turn stopping distance increased 49.1 percent over the lightly laden distance. This increase was far greater than the average increase of the other vehicles (3.4 percent) and its cause is unknown. The test driver's steering and brake inputs were nearly identical for both loading



**Figure 16. J-turn stopping distances observed on dry asphalt. Test vehicles were fully laden to their respective GVWRs.**

conditions, yet the vehicle's braking performance differed significantly.

#### HUMAN FACTORS CONSIDERATIONS

Each test vehicle provided the driver with brake pedal and aural feedback while the ABS was cycling. The test driver would often experience vibration and oscillation of the pedal and easily hear the operation of the solenoid valves and ABS pump motor. The extent to which these signals were in evidence, however, varied from vehicle to vehicle. Even the vehicle whose ABS had virtually transparent pedal feedback presented the driver with very apparent aural cues. The point is that in each case, the vehicle "told" the driver the ABS was operating.

What makes this interesting from a human factors standpoint is that the antilock brake systems of some vehicles were found to transmit different cues under different driving conditions. If an ABS was activated on a very low coefficient surface such as epoxy, it would go into a deep cycle to keep wheel slip at an acceptable level. The corresponding pedal feedback, on some vehicles, was much more pronounced during deep cycling and could, potentially, startle an unfamiliar or unsuspecting driver. The result, depending on the severity of the condition necessitating the brake application, could be that the driver lifts their foot and releases the brake pedal. Even if the driver reapplies the brakes, this action will result in dramatically increased stopping distances.

The preliminary results of NHTSA's Light Vehicle ABS Research Program Task 5.2 indicate that braking practice may influence a driver's ability to avoid a collision in a crash imminent situation with ABS. When combined with the fact that ABS brake pedal feedback may vary with respect to road condition, braking practice may have important implications.

An ABS allows a driver to maintain directional control of their vehicle and enhances vehicular stability while braking. However, ABS requires the driver to maintain positive force on the brake pedal throughout the entire duration of the stop. To prevent the driver from being surprised by ABS behavior and its resulting pedal feedback, if any, drivers should be encouraged to practice ABS braking. Such braking practice, however, should consist of maneuvers compatible with the driver's level of skill.

#### CONCLUSIONS

The results of this study indicate that for most stopping maneuvers, made on most test surfaces, ABS-assisted panic stops were shorter than those made with best effort or full pedal applications with the ABS disabled (see Table 4). Furthermore, the vehicular stability during these stops was almost always found to be superior with ABS. Although it was not specifically quantified in this study, the absence of excessive yaw while braking enhanced the ease at which the driver could maintain lane position, especially when compared to stops made with panic brake applications and the ABS disabled on split-mu and low coefficient surfaces.

The one systematic exception to this trend occurred on the loose gravel surface, where stopping distances with ABS were extended by an overall average of 27.2 percent over the disabled ABS full pedal application stops. The ABS-induced stopping distance increases were recorded for each vehicle at both loading conditions. Braking performance on this surface therefore comprises an area in which future efforts to improve ABS might be focused.

The fact that there exists a condition in which ABS actually proves to be universally detrimental proves compromises in ABS design exist. Most passenger vehicles spend much more time on smooth, paved roads than they do traveling over deformable surfaces such as gravel. Optimizing ABS behavior for such surfaces would likely involve increasing the amount of allowable longitudinal wheel slip. This could, however, dramatically reduce a vehicle's ability to turn during an ABS-assisted stop, thereby reducing one

of the fundamental attributes of ABS (enabling the driver to effectively brake and steer simultaneously).

This study also establishes that antilock brake systems include compromises of stopping distance versus vehicular stability. Most antilock brake systems maintain vehicular stability while braking by minimizing excessive yaw. In a curve, this stability may be created by sacrificing the shortest attainable stopping distance. With this said, most test vehicles (only one exception was observed) were stopped in shorter distances with ABS than with ABS disabled best effort attempts for maneuvers that involved braking and steering (or steering and braking). Under these conditions, ABS prevented wheel lockup and minimized yaw for each of the nine vehicles.

It was not the intent of this study to compare individual vehicles or antilock brake systems to one another. The test matrix was designed to examine the influence ABS has on a given vehicle's braking performance. Individual system comparison would have necessitated multiple samples of test vehicles identical in every way but ABS. Environmental conditions and test surface temperatures would also have been required to be held constant throughout the testing time line. Due to the time required for complete

instrumentation and the number of vehicles in the test fleet, such an evaluation would not have been possible.

Testing seems to indicate the increase in single driver run-off-road crashes is not due to the performance of ABS hardware. Preliminary investigation of NASS CDS crash reports (Task 3 of NHTSA's Light Vehicle ABS Research Program) shows that crashes occur most often on dry, paved roadways. Test track results, however, revealed that ABS performance was generally superior to disabled ABS performance over these surfaces. The varying brake pedal cues generated during an ABS-assisted stop (observed during testing), and the possible lack of driver familiarity with them, do provide some potentially valuable insight into the problem, however, as noted in section 7.0 of this report.

A definitive answer as to why the increase in ABS equipped, single-vehicle, run-off-road crashes exists remains elusive. NHTSA's Light Vehicle ABS Research Program will continue its exploration of all plausible reasons as to why the crash data studies do not show that ABS is improving automobile safety. Tasks 1 through 5 are currently underway, and the results will be forthcoming.

**Table 4.**  
**ABS Performance Summary**

Surface	ABS Stopping Distance Benefit (or Disadvantage) Over the Shortest non-ABS Stop (%)	
	Lightly Laden	Fully Laden
Dry Concrete Straight Line	9.8	12.7
Wet Polished Concrete Straight Line	16.7	23.1
Wet Asphalt Straight Line	11.4	17.2
Wet Jennite Straight Line	17.6*	26.6
Grass Straight Line	(7.1)*	6.9
Loose Gravel Straight Line	(30.0)*	(24.6)
ABS Test Pad #0	7.6	11.6
ABS Test Pad #1	6.2	10.3
ABS Test Pad #2	6.1	10.9
ABS Test Pad #3	4.6*	7.9*
Wet Asphalt/Wet Epoxy Split-mu	11.3	11.4
Dry Asphalt Curve	11.9	19.5
Wet Jennite Curve	18.9*	32.4

\*Percentage calculated using eight test vehicles.

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## REFERENCES

Macher, F. E., "Safety is a Standard, Not An Option," Remarks to Auto Press Association. Detroit, MI. November 12, 1997.

Farmer, C., Lund, A., Trempel, R., and Braver, E. R., "Fatal Crashes of Passenger Vehicles Before and After Adding Antilock Brake Systems." Arlington, VA: Insurance Institute for Highway Safety; 1996

Hertz, E., Hilton, J., and Johnson, D., "An Analysis of the Crash Experience of Passenger Cars Equipped with Antilock Braking Systems," NHTSA Technical Report, DOT HS 808 279, May 1995.

Evans, L., "ABS and Relative Crash Risk Under Different Roadway, Weather, and Other Conditions," SAE paper 950353. Warrendale, PA: Society of Automotive Engineers; 1994.

Kahane, C., "Preliminary Evaluation of the Effectiveness of Antilock Brake Systems for Passenger Cars," NHTSA Technical Report, DOT HS 808 206, December 1994.

Hiltner, E., Arehart, C., and Radlinski, R., "Light Vehicle ABS Performance Evaluation--Phase II," NHTSA Final Report, DOT HS 807 924, May 1992.

Hiltner, E., Arehart, C., and Radlinski, R., "Light Vehicle ABS Performance Evaluation," NHTSA Final Report, DOT HS 807 813, December 1991.

American Society for Testing and Materials, "Standard Test Method for Determining Longitudinal Peak Braking Coefficient of Paved Surfaces Using a Standard Reference Test Tire, Section 4--Construction, Vol. 04.03--Road and Paving Materials; Vehicle-Pavement Systems, 1996.

American Society for Testing and Materials., "Standard Specification for a Radial Standard Reference Test Tire," 1996 Annual Book of ASTM Standards, Section 4--Construction, Vol. 04.03--Road and Paving Materials; Vehicle-Pavement Systems, 1996.

American Society for Testing and Materials., "Standard Test Method for Skid Resistance of Paved Surfaces Using a Full-Scale Tire," 1996 Annual Book of ASTM Standards, Section 4--Construction, Vol. 04.03--Road and Paving Materials; Vehicle-Pavement Systems, 1996.

American Society for Testing and Materials., "Standard Specification for Standard Rib Tire for Pavement Skid-Resistance Tests," 1996 Annual Book of ASTM Standards, Section 4--Construction, Vol. 04.03--Road and Paving Materials; Vehicle-Pavement Systems, 1996.

Society of Automotive Engineers, Inc., "Stopping Distance Test Procedure--SAE J299 SEP93." 1996 SAE Handbook, Vol. 2--Parts and Components, 1996.